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THE IMPLICATIONS OF COAL DEVELOPMENT ON THE ATMOSPHERIC ENVIRONMENT AND PLANT ECOSYSTEMS OF SELECTED SITES IN WESTERN NORTH DAKOTA

DOCUMENT 2B
AN AIR POLLUTION STUDY FOR FOSSIL-FUEL POWER PLANTS

to:
SURFACE ENVIRONMENT AND MINING
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AGRICULTURAL EXPERIMENT STATION
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AN AIR POLLUTION STUDY FOR FOSSIL-FUEL POWER PLANTS

A Report To:

Surface, Environment and Mining (SEAM)
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(Cooperative Agreement No. 16-418-GR)

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1. INTRODUCTION

The U.S. Environmental Protection Agency (EPA) has a mandate from Congress to administer, implement, and enforce the articles of the Clean Air Act. Congress amended the act in 1970 to establish strict requirements and timetables for cleaning the air. Where health-related standards were concerned, cost and difficulty of control were not to be issues in establishing either the standards or the compliance schedules to meet them.

As required by the amendments, EPA promulgated primary (health-related) and secondary (welfare-related) ambient-air-quality standards in April 1971 for the several air pollutants, including SO_2. SO_2 emission limits for new stationary sources were pegged at 1.2 lb/million Btu for coal-fired plants; 0.8 lb/million Btu for oil-fired plants.

By mid-1972 the states had adopted, and EPA had approved, implementation plans that established emission requirements for most sources that needed to be controlled to meet ambient standards. Because power plants emit roughly 60% of all SO_2 - they emitted over 17 million tons in 1972 - they were included among the sources requiring control.

This report presents the results of air pollution study for fossil-fuel power plants. It includes a survey of air pollution control methods. Of these methods, the use of tall stack to disperse the air pollutants is frequently applied. Because of this reason efforts have been made to determine the relationships between the ground-level concentration levels and the stack design parameters. This report will serve as the reference which is needed in understanding the dispersion models.

2. SURVEY OF CONTROL METHODS

Among the air pollutants emitted from fossil-fuel power plants. SO_2 is the most serious one. Table 2-1 shows the effects of SO_2 on health by level of response. In general illness from SO_2 may be acute (short-lived) or chronic (usually permanent and irreversible). Chronic bronchitis may develop in persons exposed to even moderate levels of SO_2 over many years — an exposure range of 100-350 $\mu g/m^3$ with associated particulate levels of 66 - 365 $\mu g/m^3$.

The effects of SO_2 on vegetation has been thoroughly investigated and mechanisms explaining how SO_2 is toxic to plant life are fairly well accepted. A few plants are resistant (potatoes, onions, corn), while others are unduly sensitive (alfalfa, barley, wheat). Even sensitive vegetation can withstand 0.05 ppm of SO_2 indefinitely, not incurring chronic injury until levels of 0.1-0.3 ppm are reached, with acute injury above 0.3 ppm. Prolonged exposure to SO_2 will also cause corrosion, and damage to metals, paints and clothing. Separate reports will address to the effects of the probable changes in air quality on plant ecosystems.

In the past few years various methods of controlling SO_2 concentration levels have been proposed. They seem to group themselves from fuel selection to intermittent control of emitted SO_2:

1. Selecting low-sulfur fuels to avoid high SO_2 generation during combustion.
2. Converting high-sulfur coal to oil or gas, removing most of the sulfur in the process.
3. Capturing SO_2 within the boiler immediately after combustion of high-sulfur coal.

Table 2-1

Effects of SO_2 on Health by Level of Response

Level of Response	Sulfur Dioxide		Sulfates
	g/m^3	ppm	g/m^3
Death	500-1000	0.20-0.40[a]	No data
Illness (acute, chronic)	80-275	0.03-0.11[a]	7-14[a]
Functional changes Preceding disease	90-120	0.035-0.45[b]	9-11[a]
Changes of uncertain Significance	500-1000	0.20-0.40[c]	250[c]
Pollutant burdens	No data	No data	No data

a. 24-hour average.

b. Annual average.

c. Experimental studies.

4. Removing SO_2 just ahead of the stack, following combustion of high-sulfur coal.
5. Controlling SO_2 concentration through stack discharge to atmosphere.

It should be pointed out that "high-sulfur" coal, in our context, means coal whose combustion leads to SO_2 emissions higher than EPA or, in some cases, state standards. In the following is a summary of the SO_2 removal processes applicable to the power electric-generating system according to the principles of operation:

1. Dry metal oxide or carbonate processes.
2. Wet limestone processes.
3. Wet lime and magnesium processes.
4. Ammonia rerubbing processes.
5. Other aqueous scrubbing processes.
6. Activates carbon processes.
7. Direct oxidation processes.

Details of all processes are presented in Reference [13]. It is indicated that not all processes have become commercially acceptable. While removal systems effectively reduce SO_2 emission rate and thus SO_2 ground-level concentrations, they are expensive to own and to operate. One utility company study indicates that the cost of a retrofit limestone wet scrubbing system for their existing power plants would be about $40 $50/kw and the operating costs for such a system would be from 0.30-1.0 mills/kwh. [14].

Fluidized-bed combustion is the process in which SO_2 is captured within the boiler. Coal is injected into a fluidized bed of limestone within the boiler. The unit's tubes are immersed in the bed and the limestone and burning coal are suspended by the upward flowing combustion gases. A chemical reaction between SO_2 and limestone occurs removing the SO_2 from the exhaust gases. At the present time the fluidized-bed boiler is still in the development stage.

Converting high-sulfur coal to oil or gas are the processes that remove sulfur from coal before combustion. Coal-gasification processes involve reacting coal, steam, and oxygen under heat and pressure in a specially designed reactor to form a synthesis gas of hydrogen, carbon monoxide, carbon dioxide, sulfur compounds and varying amounts of methane. The sulfur compounds and other impurities are removed from the combustible gases. Both high BTU gas and low BTU gas can be made. However, high BTU gas is costly for power plant consumption. The utility companies, are generally interested on low BTU gas for combined cycle system. By current estimates, coal-conversion plants are still much more expensive than SO_2 removal systems. As time passes, the gap between these two is expected to become narrow.

Many liquefaction processes have been suggested. The following processes are among the most popular:

1. COED (FMC Corporation)
2. Gasoline (Ralph M. Parsons Co. and Consolidation Coal Co.)
3. H-Coal (Hydrocarbon Research Inc.)
4. SEACOKE (Atlantic Richfield Co.)
5. Low-Ash Coal (Pittsburgh & Midway)

Of the five projects listed above, H-Coal, Gasoline, and Low-Ash Coal

all utilize the same basic technology. They involve solvation and hydrogenation of coal with the only real difference being amount of liquid and solid fuels produced, i.e., the extent of the hydrogenation. COED is a pyrolysis based process which differs substantially from the hydrogenation process, being somewhat more akin to a coal gasification process. SEACOKE involves simultaneous fluid coking of coal and petroleum residuum. Like the coal gasification, the liquefaction process is expensive as a fuel for electric power generation.

It may be easiest and surest to avoid high SO_2 generation during combustion by selecting low-sulfur fuels. However, the availability of low-sulfur fuels (such as natural gas and oil) has become increasingly questionable. In a few years it may be the national policy that these fuels (natural gas and foreign-imported oil) will be conserved for other usages rather than for electric power generation. It should also be pointed out that the transportation cost of low-sulfur fuel from the mining area to the consumers has increasingly become significant.

Use of tall stacks to control the impact of stack emissions at ground-level is a relatively inexpensive method. Tall stacks do not reduce SO_2 emissions, but only disperse them over a larger chunk of landscape. In regard to sulfates, some experts theorize that tall stacks may actually encourage their formation. Although air-borne sulfate formation is admittedly not understood clearly at this time, experts fear that the chance it will occur is significantly increased, the longer SO_2 emissions remain air borne, as is the case when the gas is emitted from tall stacks. On the other hand, tall stacks can indeed

reduce the SO_2 ground-level concentration to the acceptable level. The health of the community is not endangered. Because of these, tall stacks are also controversial.

The Environmental Protection Agency (EPA) maintain their position that the tall stack is an interim measure for utility companies. In most cases EPA is likely to agree to use of tall stacks as long as the utilities will commit themselves to programs for permanent SO_2 removal within a realistic time frame.

3. PLUME RISE EQUATIONS

The behavior of an effluent plume in the atmosphere is a complicated process. Mathematical management of the dispersion process requires two major segments: 1. the stack effluents rise on their own momentum and buoyancy forces when atmospheric stability and turbulence are operative but their influence on plume behavior is secondary; 2. the momentum and buoyancy forces become relatively weak and the effluent plume starts to dilute by mixing with surrounding ambient air. Fundamentally, the two parameters of atmospheric system which have a strong influence on the dispension of stack gases are wind velocity and characteristics of turbulence (atmospheric stability).

An examination of any mathematical model for predicting the ground level concentrations would reveal an importance of plume rise calculations. As shown later in this report, an overestimate of plume rise by 25% will lower the prediction of the maximum ground-level SO_2 concentration by 17.5%. In this section is a very brief survey of plume rise equations available. These plume rise equations are:

Carson and Moses Equation [3]

$$\Delta H = A \frac{4.12\, V_s d + 9.22(Q_H)\frac{1}{2}}{\bar{u}} \qquad (3\text{-}1)$$

where ΔH = predicted height of rise above stack top (m)

V_s = stack exit speed (m/sec)

d = stack diameter (m)

Q_H = heat emission (10^4 cal/sec)

$\bar{u}$ = mean wind speed at stack top (m/sec)

A = stability correction

$A = 1$ if $\frac{d\theta}{dz} \geq -0.22\ ^{o}c/100m$

$A = 2.43$ if $\frac{d\theta}{dz} < -0.22\ ^{o}c/100m$

$\frac{d\theta}{dz}$ = changes of potential temperature with height from stack top to plume top.

Lucas, Moore and Spurr Equation [4]

$$\Delta H = \frac{0.7\ \alpha_n}{\bar{u}} \left(\frac{Q_n}{G_n}\right)^{1/4} \qquad (3\text{-}2)$$

where ΔH = predicted height of rise above stack top (ft)

α_n = stack height factor

α_n = 4500 for H_s = 200 ft.

= 5000 for H_s = 300 ft.

= 5500 for $H_s \geq 400$ ft.

H_s = stack height (ft)

$\bar{u}$ = mean wind speed at stack top (ft/sec)

Q_n = heat emission (megawatts)

G_n = stability parameter

$$G_n = (100\ \frac{d\theta}{dz}) / \bar{u}^2$$

$\frac{d\theta}{dz}$ = change of potential temperature with height ($^{o}c/1000$ ft)

If $\frac{d\theta}{dz}$ is zero or negative, the plume rise is suggested as

$$\Delta H = \alpha_n \left(\frac{Q_n}{\bar{u}}\right)^{\frac{1}{4}} \qquad (3\text{-}3)$$

Concawe Equation [4]

$$\Delta H = 0.047 \left(\frac{Q_H^{\,0.58}}{\bar{u}^{0.70}}\right) \qquad (3\text{-}4)$$

where ΔH = predicted height of rise above stack top (m)

Q_H = heat emission (cal/sec)

$\bar{u}$ = mean wind speed at stack top (m/sec)

Briggs Equations [11]

$$\Delta H = 1.6\, F^{1/3}\, \bar{u}^{-1} (10\, H_s)^{2/3} \qquad (3\text{-}5)$$

for neutral and unstable lapse rates,

$$\Delta H = 2.9 \left(\frac{F}{\bar{u}.s}\right)^{1/3} \qquad (3\text{-}6)$$

for stable lapse rate with wind and

$$\Delta H = 5.0\, F^{1/4}\, s^{-3/8} \qquad (3\text{-}7)$$

for stable and calm conditions

where ΔH = plume rise above top of stack

$F = \frac{T_s - T}{T_s} r^2 wg$ = buoyancy parameter

$S = \frac{g}{T} \left(\frac{d\theta}{dz}\right)$ = atmospheric stability parameter

$\bar{u}$ = wind speed

H_s = physical stack height

T_s = effluent temperature

T = ambient air temperature

r = stack inside radius

w = exit vertical velocity

g = acceleration of gravity

θ = atmospheric potential temperature

z = height

Holland Equation [1]

$$\Delta H = \frac{V_s d}{\bar{u}} \left(1.5 + 2.68 \times 10^{-3} P \frac{T_s - T_a}{T_s} d\right) \qquad (3\text{-}8)$$

where ΔH = the rise of the plume above the stack (m)

V_s = stack gas exit velocity (m/sec)

d = the inside stack diameter, m

$\bar{u}$ = wind speed, (m/sec)

P = atmospheric pressure, (mb)

T_s = stack gas temperature (^{o}k)

T_a = air temperature (^{o}k)

and 2.68×10^{-3} is a constant having units of $mb^{-1}\ m^{-1}$

Holland suggested that a value between 1.1 and 1.2 times the ΔH from the equation should be used for unstable conditions, a value between 0.8 and 0.9 times the ΔH from the equation should be used for stable conditions.

The state of the art of prediciting height-of-rise from meteorological and stack data at present is quite poor. The agreement among these equations are not always good. The factor influencing plume rise are many. In general, they are

1. gas exit velocity
2. wind velocity
3. inside diameter of stack
4. ambient air temperature
5. gas temperature
6. atmospheric stability conditions
7. stack height

It should be stressed that all these factors may not appear at the same time in the plume rise equation. In this study the Holland's equation is used for the mathematical modeling.

4. DIFFUSION EQUATIONS

Various mathematical models are used to predict the dispersion patterns of windborne pollutants emitted from an electric power generating facility. They are conveniently grouped as follows:

1. The Gaussian diffusion model and its derivatives.
2. Fluid dynamic models.
3. Empirical models.

The most widely used models are those related to the Gaussian diffusion equation and its derivatives. These equations include simple mathematical formulas which are easily understood and specified for use by the Environmental Protection Agency (EPA). Because of these, this section will only present the Gaussian diffusion equations.

Figure 4-1 indicates the coordinate system showing Gaussian distributions in the horizontal and vertical directions. The concentration of air pollutant at any location due to a single, but continuous emission source is given by the equation.

$$X(x,y,z,H) = \frac{Q}{2\pi\sigma_y\sigma_z u} \exp\left[-\frac{1}{2}\left(\frac{y}{\sigma_z}\right)^2\right] \qquad (4\text{-}1)$$

$$\left[\exp\left[-\frac{1}{2}\left(\frac{z-H}{\sigma_z}\right)^2\right] + \exp\left[-\frac{1}{2}\left(\frac{z+H}{\sigma_z}\right)^2\right]\right]$$

where X = concentration (q/m^3)

Q = source strength (q/sec)

u = wind speed (m/sec)

H = effective stack height (m)

x,y,z = space coordinates (m)

σ_y = horizontal dispersion coefficient (m)

σ_z = vertical dispersion coefficient (m)

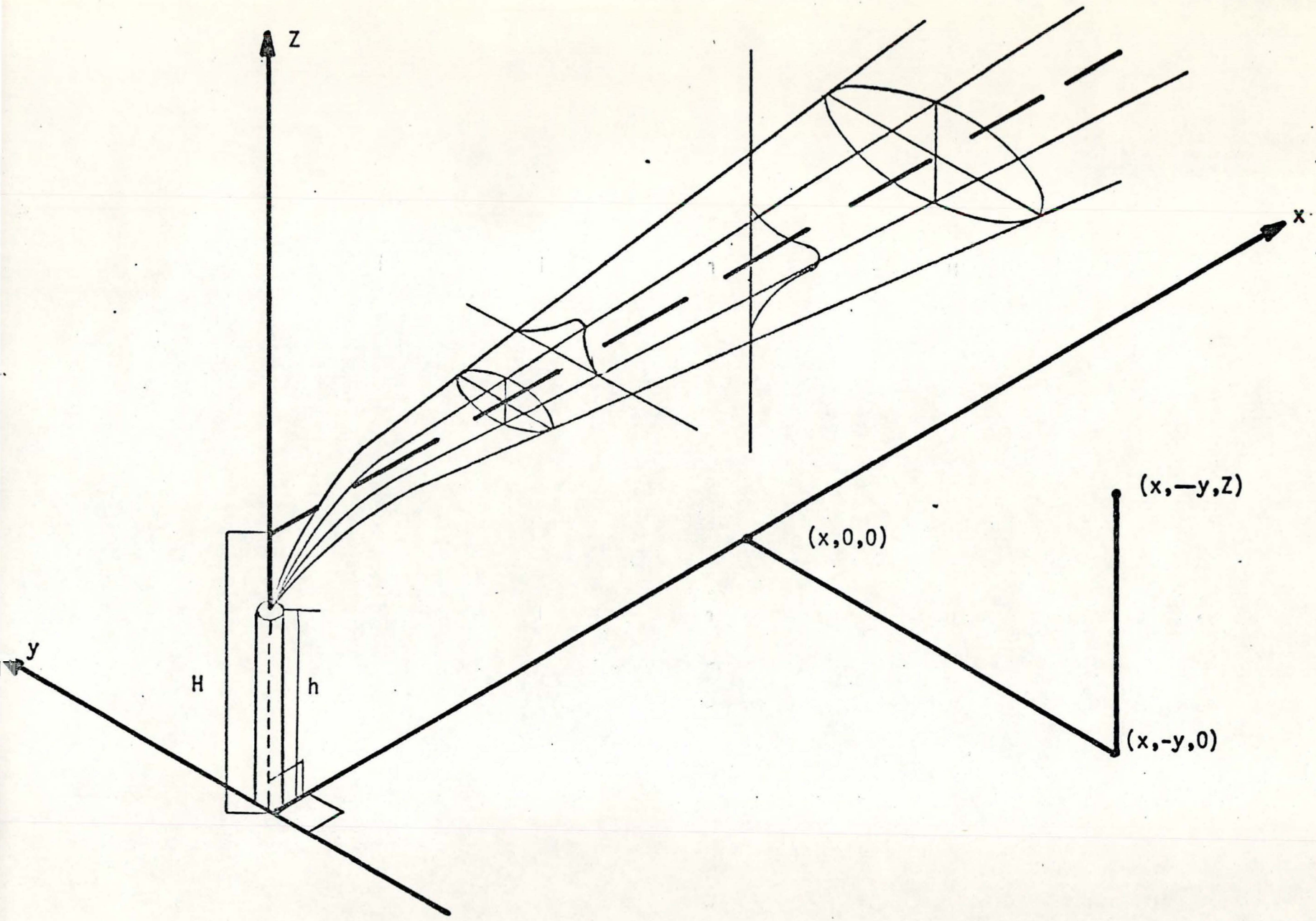

Figure 4-1. Coordinate system showing Gaussian distributions in the horizontal and vertical.

There should be some explanation about the dispersion coefficients (σ_y,σ_z). The values of σ_y and σ_z vary with the turbulent structure of the atmosphere, height above the surface, surface roughness, sampling time over which the concentration is to be estimated, wind speed and distance from the source. One can evaluate the estimates of σ_y and σ_z as a function of downwind distance from the source using Figure 4-2 and Figure 4-3. The stability classes shown in thes diagrams are defined by Turner [1] . Details are presented in Appendix A.

Eq(4-1) was prepared with the following basic assumptions.

1. Continuous emission from the source.
2. The material diffused is a stable gas or aerosal.
3. The mean wind direction specifies the X axis, and a mean wind speed representative of the diffusing layer is chosen.

It should be pointed out that Eq (4-1) can be used for estimating ground-level concentration of windborne pollutants with a certain degree of confidence only in ideal situations (flat terrain, unlimited mixing) and to some extent under limited mixing conditions. In other situations— such as thermal inversion break-up, high-wind fumigation, or complex terrain — it is well known that the Gaussian diffusion model would generate the ground-level concentration of windborne pollutants little higher than those observed.

Eq (4-1) generates the concentration levels for the sampling time 10 minutes. If it is necessary to estimate concentration levels from a simple source for the sampling time interval other than the 10 minutes

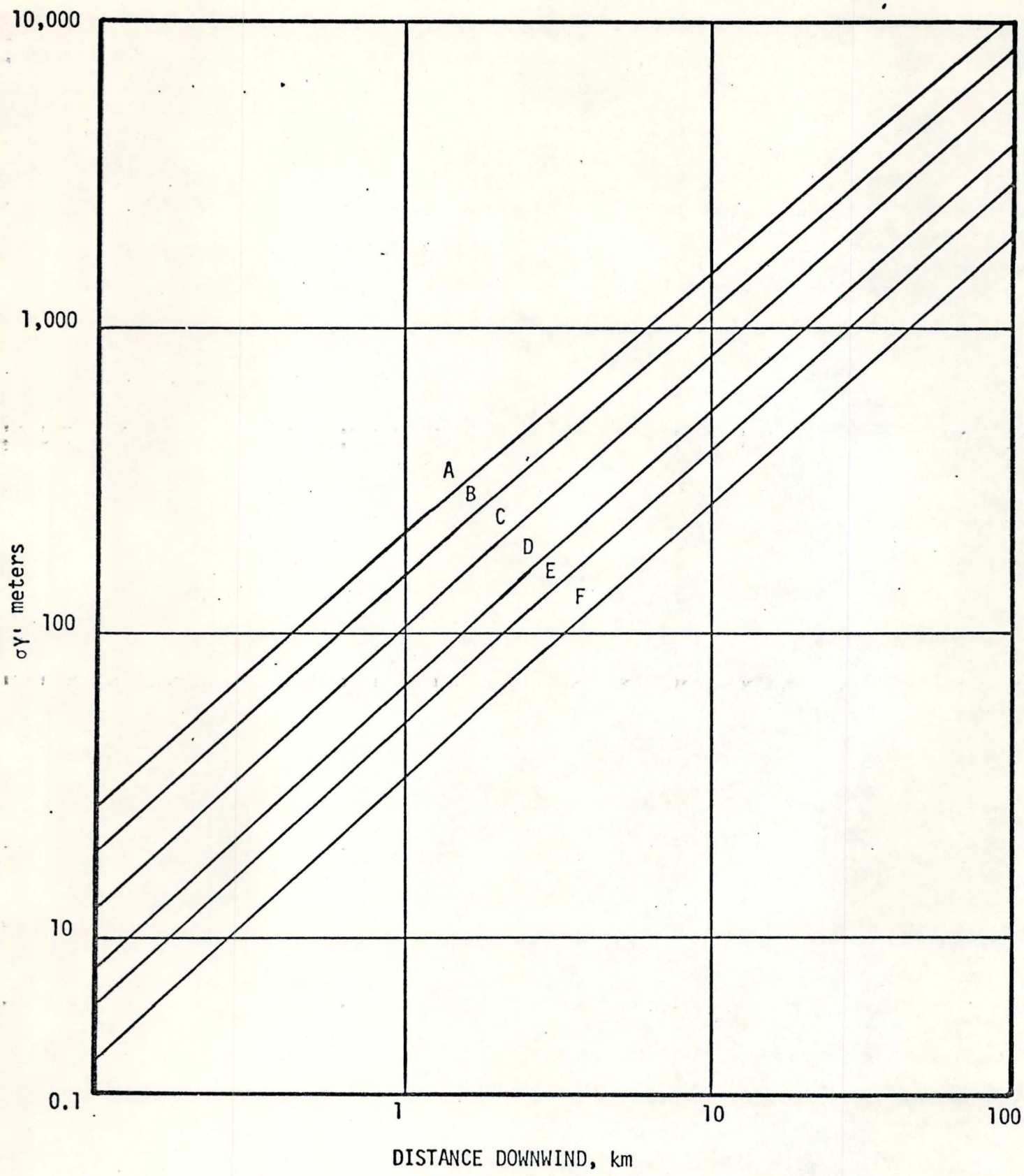

Figure 4-2. Horizontal dispersion coefficient as a function of downwind distance from the source.

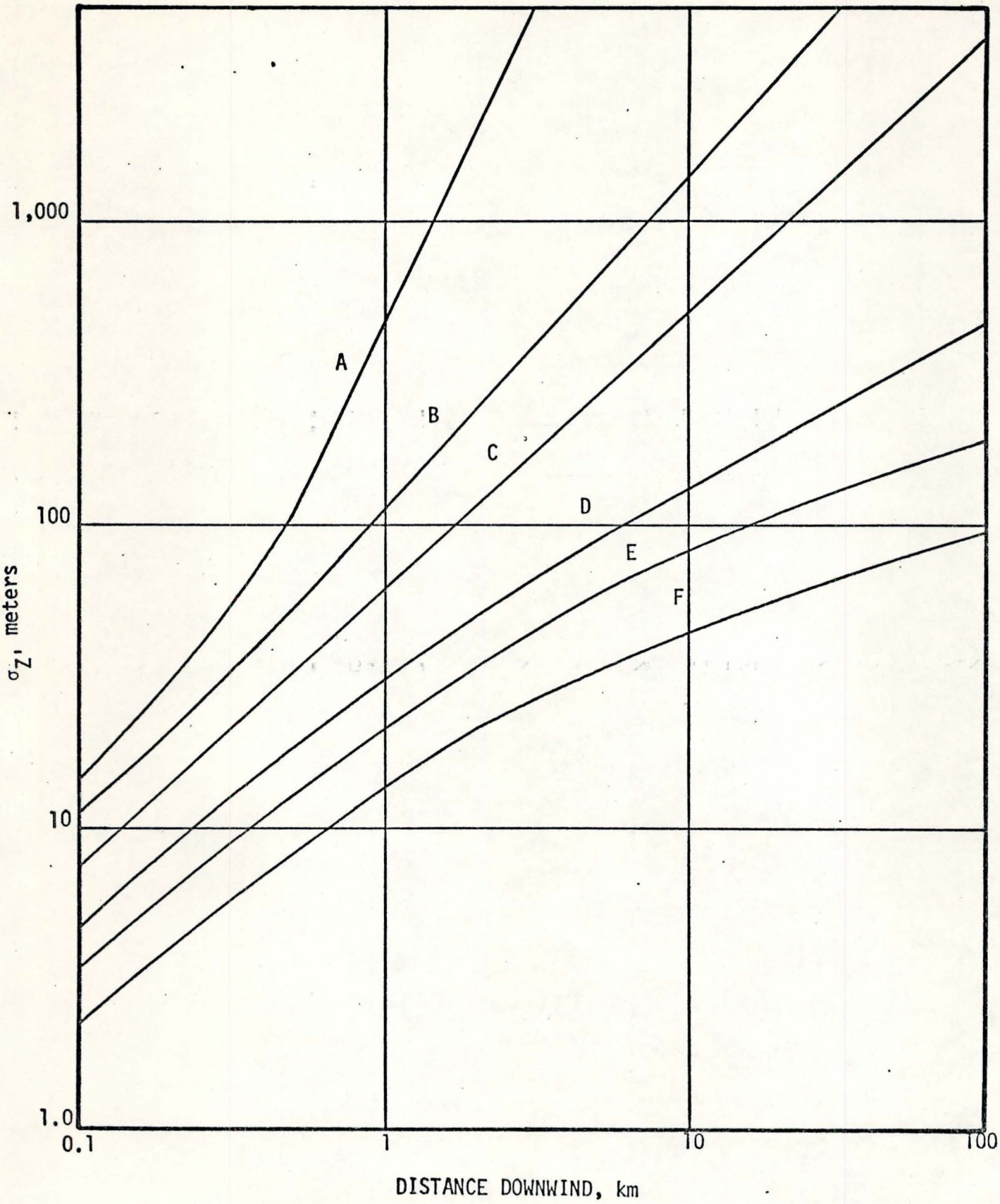

Figure 4-3. Vertical dispersion coefficient as a function of downwind distance from the source.

interval, the following equation should be used.

$$X_s = X_k \left(\frac{t_k}{t_s}\right)^p \qquad (4\text{-}2)$$

where X_s = the desired concentration level for the sampling time t_s.

X_k = the concentration level for the sampling time t_k.

t_k = sampling time A.

t_s = sampling time B.

p = constant.

Experiences indicate that p should be between 0.17 and 0.2. Eq (4-2) can be applied only for the sampling time up to 2 hours. For a longer sampling time interval the ratios shown in Table 4-1 should be used.

In this study the following equation was used to predict the maximum ground-level concentration from several stacks.

$$\overline{X}\ \text{total} = n^c\ \overline{X}\ \text{single} \qquad (4\text{-}3)$$

where n = number of stacks.

$\overline{X}$ total = concentration level due to an operation of several stacks.

$\overline{X}$ single = concentration level due to an operation of single stack.

c = constant to be determined.

For the case study presented later in this report, the constant c was set equal to 1.0. The assumption is considered conservative.

Under plume trapping conditions the concentration level will become much higher than those predicted by Eq (4-1). Bierly and Hewson [1] suggested

Table 4-1

Calculated Concentration with Sampling Time

Sampling Time	Ratio of Calculated Concentration to 3 minute concentration
3 minutes	1.00
15 minutes	0.82
1 hour	0.61
3 hours	0.51
24 hours	0.36

the use of the following equation which accounts for the multiple eddy reflection from both the ground and the stable layer:

$$\overline{X}(x,o,z,H) = \frac{Q}{2\pi\bar{u}\sigma_y\sigma_z}\left[\exp\left[-\frac{1}{2}\left(\frac{z-H}{\sigma_z}\right)^2\right]\right.$$

$$+ \exp\left[-\frac{1}{2}\left(\frac{z+H}{\sigma_z}\right)^2\right] + \sum_{n=1}^{n=J}\left[\exp -\frac{1}{2}\left(\frac{z-H-2nL}{\sigma_z}\right)^2\right.$$

$$+ \exp -\frac{1}{2}\left(\frac{z+H-2nL}{\sigma_z}\right)^2 + \exp -\frac{1}{2}\left(\frac{z-H+2nL}{\sigma_z}\right)^2$$

$$\left.\left. + \exp -\frac{1}{2}\left(\frac{z+H+2nL}{\sigma_z}\right)^2\right]\right] \qquad (4\text{-}4)$$

where L is the height of the stable layer and J = 3 or 4 is sufficient to include the important reflection. If the reflection from the stable layer is omitted, the following equation can be used:

$$\overline{X}(x,y,z,H) = \frac{Q}{\sqrt{2\pi}\,\sigma_y\, L\, \bar{u}} \exp\left[-\frac{1}{2}\left(\frac{y}{\sigma_y}\right)^2\right] \qquad (4\text{-}5)$$

for $x > 2x_1$; x_1 is where $\sigma_z = 0.47L$.

It is seen in Eq (4-5) that the concentration level is uniformly distributed between the ground-level and the stable layer. For the distance from the emission source less than x_1 , Eq (4-1) should be used for calculations. For distances between x_1 and $2x_1$, the best approximation to the ground-level centerline concentration is read from a straight line drawn between the concentrations for points x_1 and $2x_1$ on a log-log plot of ground-level centerline concentration as a function of distance.

Under the inversion break-up conditions the concentration level will also become much higher than those predicted by Eq (4-1). The following equation is used to estimate the fumigation concentration:

$$X_F\,(x,y,o,H) = \frac{Q}{\sqrt{2\pi}\; u\; \sigma_{yF} h_i} \exp\left[-\frac{1}{2}\left(\frac{y}{\sigma_{yF}}\right)^2\right] \qquad (4\text{-}6)$$

where $h_i = H + 2\sigma_z$

and $$\sigma_{yF} = \frac{2.15\;\sigma_y\;(\text{stable}) + H \tan 15^o}{2.15} \qquad (4\text{-}7)$$

or $$= \sigma_y\;(\text{stable}) + \frac{H}{8} \qquad (4\text{-}8)$$

It should be noted that Eq (4-8) can not be applied near the stack. More information is presented in Reference [1] .

The average annual concentration is estimated by the following equation.

$$\overline{X}\,(x,\theta) = \sum_s \sum_n \left[\frac{2Q\;F(\theta,s,n)}{\sqrt{2\pi}\;\sigma_{zs}\;u_n\;(\frac{2\pi x}{16})} \exp\left[-\frac{1}{2}\left(\frac{H_u}{\sigma_{zs}}\right)^2\right]\right] \qquad (4\text{-}9)$$

where $F(\theta, s, N)$ = the frequency during the period of interest that the wind is from the direction θ, for the stability condition s, and the wind speed class n.

σ_{zs} = the vertical dispersion parameter evaluated at the distance x for the stability condition s.

u_n = the representative wind speed for class n.

H_u = the effective height of release for the wind speed u_n.

Eq (4-9) indicates that the average annual concentrations can be predicted by calculating the concentrations for specific climatological conditions and then, weighting each concentration by its relative frequency of occurrence. The calculations will be straight-forward, but lengthy.

The models recommended by the Environmental Protection Agency (EPA) are based upon the Gaussian diffusion equations and its derivatives. Three models have been set up in the Computer Center of North Dakota State University. These models are PIDIS (Point Distance) PTMAX (Point Maximum), and PTMTP (Multiple Points). The user's manuals were prepared and presented in the previous report [12] . With the manuals, those who are interested can easily apply these computer programs.

5. GENERAL SCHEME FOR STACK HEIGHT STUDY

The general objective of stack height study is to determine the stack height by which the air pollutants emitted from the plant would not generate under the local meteorlogical conditions the ground-level concentrations higher than those specified by the Federal, the state and the local governments. Obviously the study should at least include the following elements.

1. Collection of meteorological data for plant site
2. Selection of mathematical dispersion models
3. Set-up of calculational scheme
4. Special studies related to optimum plant design, if necessary.

As indicated in the previous sections the meteorological conditions at plant site will affect the plume rise as well as plume pattern. Adequate air-quality assessment must address all situations on an individual basis, with most of the emphasis being put on the limiting case or cases yielding the highest ground-level concentration of airborne pollutants.

Table 5-1 shows some of the key meteorological data necessary for a stack height study. The ambient temperatures will enable the engineer to calculate the range of variation of the buoyancy parameter being applied in plume-rise calculations. Temperature gradients are also used in the calculation of the stability parameter.

Classification of temperature profiles accounts for the frequency of ground-based thermal inversion, their heights and intensities; elevated stable layers, their frequency, vertical extent, and intensity; and other

Table 5-1

Meteorological Data Used in Air-Quality Analysis

METEOROLOGICAL PARAMETERS	PURPOSE
Climatological data:	Climatological data:
Minimum, mean, and maximum ambient temperature on a monthly, seasonal and annual basis	Used in plume-rise calculations
Minimum, mean, and maximum ambient relative humidity on a monthly, seasonal, and annual basis	Used in visibility calculations
Diffusion meteorology:	Diffusion meteorology:
Hourly wind speed, wind direction, and atmospheric stability	Used in short- and long-term diffusion calculations
Monthly, seasonal, and annual frequency distribution of wind speed and direction according to Pasquill stability classes at stack or mean plume height	Used in short- and long-term diffusion calculations
Daily, monthly, seasonal, and annual minimum, mean, and maximum mixing depths	Used in short- and long-term diffusion calculations, especially in determining trapping potential
Monthly and seasonal heights of ground-based thermal inversions, including their strength	Used in calculating plume capability to penetrate through these inversions and in fumigation calculations
Hourly stability and wind direction data	To determine whether fumigation is possible or not
Wind speed and direction persistence according to Pasquill stability classes	To determine whether or not the plume will reach a certain downward point, and for how long a certain ground-level concentration will last in one direction
Frequency of occurrence of strong winds	To determine the potential of plume downwash

temperature distributions such as neutral, stable, etc. With profile classification, plume penetration through or into stable layers can be elevated, thus allowing frequency of occurrence of plume fumigation, plume trapping, and unlimited plume mixing to be estimated.

The sources for meteorological data collection are U.S. weather stations and an on-site meteorological program. While the information from U.S. weather stations are representative of the site in the general sense, the on-site meteorological program will provide the data more useful for a diffusion study. There is no doubt that the on-site program is expensive and time consuming.

The selection of mathematical dispersion models is not a simple matter. At this moment no model is perfect. Each model has its limitations and restrictions. Because of these, it is necessary to have model calibration and validation. To have a good prediction in some cases, a new model may have to be developed for the situation under concern. This model may be of empirical and statistical nature, incorporating key terms from the physical viewpoint.

The values predicted by the Gaussian diffusion models are generally acceptable. However, care should be exercised in the interpretation of these calculated concentrations. Concentration estimates may be expected to be within a factor of three

Table 5-2 presents a general calculational scheme. It is seen that a stack height study consists of an evaluation of ground-level concentration of wind-borne pollutants (both short term and long term). Besides the meteorological parameters, emission inventory, stack parameters, and stack layout are of great importance. In determining source strength, plant operating capacity and modes have to be considered

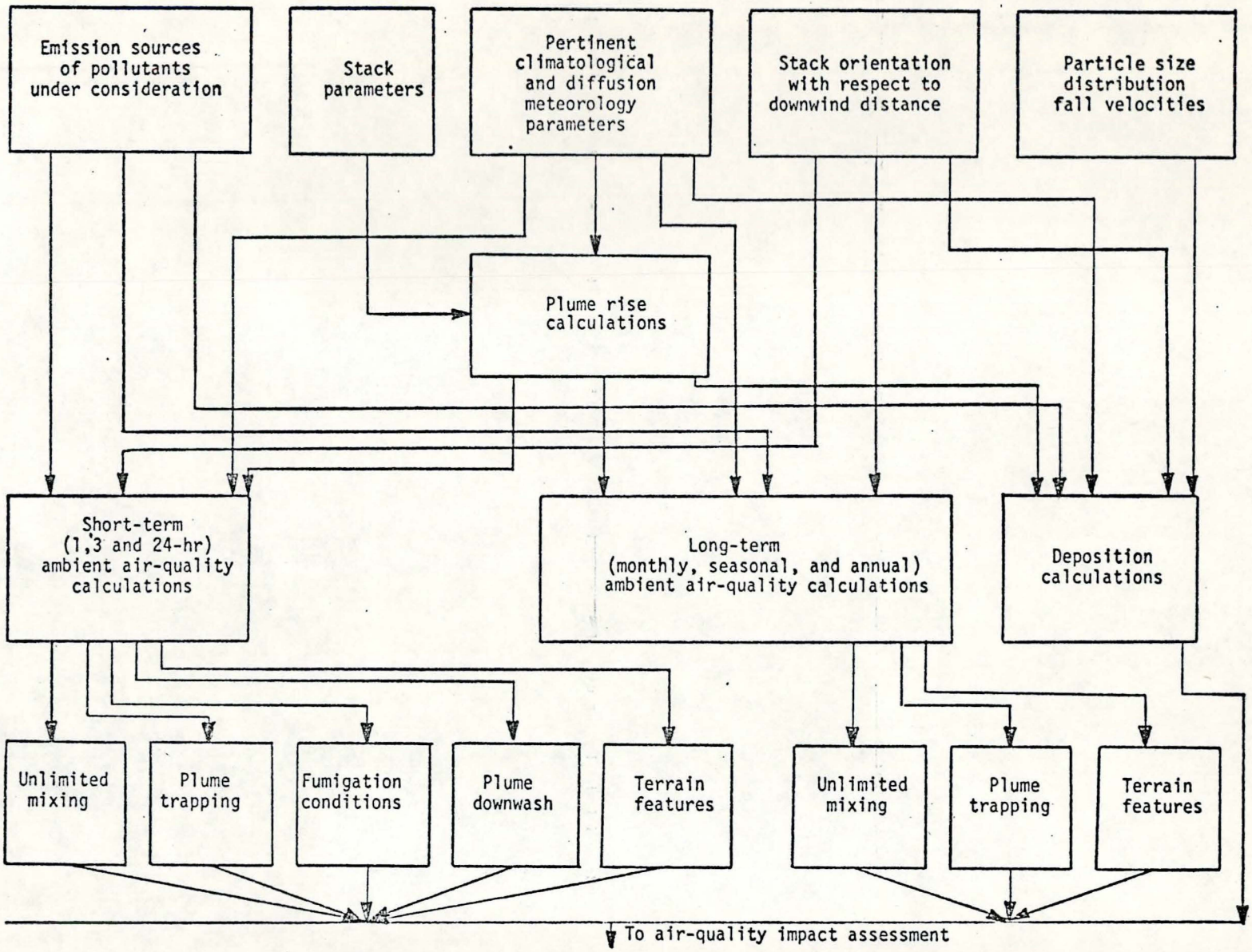

Table 5-2. Input data and calculation scheme used in air-quality evaluation for a proposed utility stack

along with fuel characteristics.

Calculations should be made with worst-source characteristics, and should account for operation at full load. In determining the potential impact at full load, the frequency of occurrence of worst-source emissions should be related to the frequency of occurence of plant operation at full load and to worst meteorological conditions. That is, the probability of having all three events should be determined.

It should be pointed that the calculational scheme is of iterative nature. Certain stack parameters have to be assumed first. Then, the ground level concentrations are calculated and compared with the applicable standards. These procedures should be repeated until the stack parameters (including the stack height) are such that the ground-level concentrations are safely below the federal, the state and the local limits.

As mentioned in the previous sections most diffusion models can only predict the ground-level concentrations with a certain degree of confidence , when the plant site is on the flat terrain. If the plant site conditions are different such as those in the hilly area or those in the area close to the large water bodies, special studies must be made for dispersion pattern. These studies may involve wind tunnel experiments.

Special studies are required when the stack is built near the tall structure which gives rise to aerodynamically disturbed air flow and inhibit a good dispersion.

In general special studies are needed when accurate prediction of ground-level concentrations is desired. However, these studies are always expensive and time consuming.

6. A CASE STUDY

This section presents the results of a case study to determine the required stack height and to predict the concentration levels of pollutants at various distance from a power station, in the State of Arkansas. The computations and conclusions are based on an analysis of the area meteorological conditions, satisfaction of regulatory standards, emission data and interaction of the four stack plant. The results are considered conservative in that unit loads of 100%, critical wind speeds and constant north or south wind direction were assumed.

In this case study consideration was given to the possibility of selecting different stack heights for different units and using one stack for two generating units. Also included were the recommendations on further works for the power station.

This case study will serve as an illustration how the stack height is affected by the parameters as mentioned in the previous sections.

6-1. Required Stack Height for Minimizing Ground Level SO_2 Concentrations

A. Input Information

A power company is planning to construct four identical power generating units in the State of Arkansas. It is possible in the near future that two more units would be added. Each unit has a net capacity of 800 MW.

Table 6-1 contains the emission and stack information provided for this case study. All data are for one unit at the full load.

Shown in Table 6-2 is the emission standards and air quality standards that the Environmental Protection Agency (EPA) has established for new stationary sources. The State of Arkansas also established the air quality standards. They are summarized and shown in Table 6-3. Since the State has a more restricted standards than the EPA, the State standards will be used as the allowable air quality standards in this study.

Since there is no climatological data available for the power station under consideration, the data of Little Rock will be used. Presented in Table 6-4 are the windrose tabulations. For the computations of this study the local atmospheric stability has been predicted with the available climatological data. Table 6-5 indicates the percent frequency occurance of stability class. The stability class B has been preselected as the design condition. More information on atmospheric stability categories can be found in Appendix A.

Table 6-1

Emission Data

SO_2 Emission Rate	11,130 lbs/hr.
NO_x Emission Rate	6,354 lbs/hr. *
Particulate Emission Rate	907.8 lbs/hr. *
Effluent Temperature	280 F
Ambient Air Temperature	80 F
Inside Stack Diameter	27 ft.
Exit Velocity	90 ft/sec.

* Based on the EPA emission standard and the actual rate is much less than that indicated.

Table 6-2

EPA Emission Standards and

Air Quality Standards for New Stationary Sources

Source	Pollutant	Emission Standard		Secondary Air Quality Standard	
		Conc.	Averaging Time, hr.	Conc ug/m^3	Averaging Time
Fossil fuel	Particulates	0.1 lb/mil Btu	2	150	24 hr.
Fired steam	Sulfur dioxides				
Generator	Liquid fossil-fuel	0.8 lb/mil Btu	2	260	24 hr.
	Solid fossil-fuel	1.2 lb/mil Btu	2	260	24 hr.
	Nitrogen Oxides				
	Gasseous fossil-fuel	0.2 lb/mil Btu	2	100	Annual
	Liquid fossil-fuel	0.3 bl/mil Btu	2	100	Annual
	Solid fossil-fuel	0.7 lb/mil Btu	2	100	Annual

Table 6-3

Summary of State Standards

1. The peak ground level concentration of sulfur dioxide (30 min. average) shall not exceed 0.2 ppm in any 24 hour period.

2. The maximum concentration (24 hour average) of suspended particulate matter shall not exceed 75 micrograms per cubic meter.

3. The maximum concentration (30 min. average) of suspended particulate matter shall not exceed 150 micrograms per cubic meter.

4. The particulate fallout contributed from the plant shall not exceed 15 tons per square mile per month.

5. The number of particles larger than 60 microns in diameter downwind of the premises shall not exceed 120 per square centimeter for 24 consecutive hours.

Table 6-4

Windrose Tabulations

Direction		Spring & Fall		Winter		Summer		Annual	
		Wind mph	Freq.	Wind mph	Freq.	Wind mph	Freq.	Wind mph	Freq.
N	36	8.7	.0255	10.0	.0259	7.3	.0145	8.7	.0220
	01	9.0	.0182	9.6	.0185	8.3	.0072	9.0	.0145
	02	8.2	.0237	9.8	.0333	8.6	.0109	8.9	.0226
	03	9.6	.0109	10.3	.0593	8.0	.0181	9.3	.0294
NE	04	7.8	.0310	10.8	.0333	6.7	.0217	8.4	.0287
	05	8.6	.0328	8.7	.0370	7.0	.0290	8.1	.0329
	06	7.4	.0474	9.5	.0444	6.6	.0435	7.8	.0451
	07	7.7	.0219	7.6	.0481	6.6	.0362	7.3	.0354
	08	6.5	.0237	6.2	.0222	5.4	.0181	6.0	.0213
E	09	7.9	.0128	7.6	.0185	5.3	.0254	6.9	.0189
	10	7.8	.0164	7.5	.0074	5.8	.0435	7.0	.0224
	11	7.0	.0128	6.7	.0148	5.5	.0217	6.4	.0164
	12	5.2	.0109	5.9	.0148	6.1	.0254	5.7	.0170
SE	13	6.7	.0273	6.4	.0185	5.4	.0181	6.2	.0213
	14	6.9	.0364	7.6	.0148	5.2	.0326	6.6	.0279
	15	6.1	.0273	8.0	.0481	5.0	.0290	6.4	.0348
	16	6.6	.0474	6.2	.0148	5.6	.0290	6.1	.0304
	17	7.1	.0364	7.3	.0259	7.0	.0399	7.1	.0341
S	18	8.0	.0383	6.9	.0444	7.4	.0399	7.4	.0409
	19	9.1	.0455	8.4	.0444	6.0	.0435	7.8	.0445
	20	8.3	.0710	10.9	.0222	6.6	.0652	8.6	.0528
	21	8.7	.0346	9.4	.0407	7.2	.0906	8.4	.0553
SW	22	8.0	.0383	8.3	.0519	8.4	.0870	8.2	.0591
	23	8.4	.0437	10.0	.0333	8.1	.0435	8.8	.0402
	24	8.3	.0200	11.1	.0407	7.9	.0435	9.1	.0347
	25	9.4	.0219	10.4	.0148	7.7	.0181	9.2	.0183
	26	9.9	.0237	8.3	.0148	6.9	.0290	8.4	.0225
W	27	8.6	.0219	8.3	.0111	6.0	.0072	7.6	.0134
	28	9.5	.0164	11.3	.0111	7.7	.0109	9.5	.0128
	29	10.1	.0310	10.6	.0185	6.4	.0217	9.0	.0237
	30	8.9	.0237	11.1	.0333	9.2	.0072	9.7	.0214
NW	31	9.9	.0164	9.4	.0222	7.8	.0036	9.0	.0141
	32	9.3	.0237	10.1	.0259	6.0	.0036	8.5	.0177
	33	10.4	.0255	11.8	.0222	6.8	.0036	9.7	.0171
	34	9.4	.0200	11.4	.0296	7.2	.0145	9.7	.0214
	35	9.1	.0219	10.0	.0222	7.3	.0036	8.8	.0159

Table 6-5 **

Percent Frequency Occurrence of Stability Standards

Wind Vel. (mph)	Stab. Class	N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW
≤5	A	.055	.110	.074	.103	.111	.204	.258	.148	.186	.116	.148	.167		.034	.086	.086
	B	.021	.105	.298	.125	.252	.280	.270	.173	.220	.212	.178	.124	.063	.048	.109	.063
	U_1*	.160	.312	.331	.512	.318	.679	.791	.656	.665	.273	.677	1.587	.428	.042	.085	.111
	U_2*	.172	.169	.367	.388	.343	.509	.417	.442	.346	.519	.228	.552	.118	.119	.057	.161
6-14	A		.131	.119	.218	.296	.267	.327	.266	.097	.145	.245	.382	.042	.028	.011	.097
	B	.934	.701	.802	.949	1.249	1.394	1.233	1.175	1.640	1.185	1.392	1.704	.693	.479	1.018	1.012
	C	.655	.575	1.394	.966	1.075	1.371	1.239	1.143	1.818	1.644	1.065	1.202	.561	.710	.978	.909
	D	1.170	1.281	1.033	.630	.571	.381	.567	.646	1.646	1.419	1.019	.620	.372	.722	.969	.632
	E	1.061	.564	.771	.803	.475	.479	.544	.720	1.439	.676	.959	1.899	.859	.320	.356	.349
	F	.173	.402	.337	.272	.076	.279	.284	.479	.984	.637	.992	2.119	1.197	.237	.115	.154
15-24	C	.140					.028	.006	.013	.131	.237	.245	.196	.055	.140	.537	.263
	D	.516	.162	.262	.217	.110	.117	.125	.212	.372	.697	.612	.196	.187	.401	.479	.338
>25	C																
	D										.029	.006			.034		

* U_1 and U_2 are unclassified.

** prepared by Mr. Knepp.

B. Calculational Method

The method recommended by D. B. Turner (1) was used to determine the required stack height. The basic procedures of this method are:

1. Calculate the rise of the plume above the stack at various wind speeds.
2. Assume a stack height and calculate the effective stack height at various wind speeds.
3. Predict the ground-level SO_2 concentrations at various distances from the stack.
4. Determine the maximum ground-level of SO_2.
5. Compare the calculated maximum ground-level SO_2 concentration with that specified in the EPA and state standards. If the calculated level is higher than the allowable, assume a new stack height and repeat the steps 2, 3, 4 and 5.

To predict the maximum ground-level concentration from several stacks, the following approximation equation was used:

$$\overline{X}_{total} = n^c \times \overline{X}_{single}$$

where n = number of stacks

c = constant to be determined

In this study the constant c was set equal to 1.0. This assumption is considered conservative.

The maximum or axial time-mean concentration of effluent generally decreases with increasing sampling time. This is due to the fact that the lateral dispersion of effluent increases with time. The functional relationship can be shown as

$$\frac{\overline{X}}{\overline{X}_r} = \left(\frac{t_r}{t}\right)^n$$

where $\overline{X}$ is the desired concentration estimate for the sampling time t, $\overline{X}_r$ is the concentration estimate for the reference sampling time t_r. In this study the exponent n is set equal to 0.2 as recommended by D. B. Turner [1].

C. Stack Height Selection

The recommended stack height for the first four units is 800 feet at this time. This stack height would satisfy all stipulated ground-level concentration limits. The detailed comparisons of EPA ambient air quality standards with the present State standards and the calculated plant contribution are seen in Table 6-6. It should be pointed out that the calculated plant contribution indicated in the last column, is the maximum ground-level concentration of pollutant due to the plant operation. This maximum level would occur only at the cirtical wind speed and at a certain wind direction. The plant load has been assumed to be 100%. The recommended stack height will provide more safety margin in terms of ground-level concentrations if the actual conditions are deviated from the above assumed conditions or if the atmospheric stability conditions are more neutral and stable than the class B.

In the selection of stack height the regulatory restriction on the maximum ground-level SO_2 concentration is most controlling. Because of these facts, it was decided to size the stacks to meet the sulfur dioxide requirements. The concentration of other constituents would thereby be within the applicable restrictions.

Table 6-6

Comparison of Environmental Protection Agency (EPA) Ambient Air Quality Standards with Present State Standards and the Calculated Plant Contribution

	EPA Limits		State Limit	Calculated Plant Contribution
	Primary	Secondary		
Sulfur Dioxide				
Maximum Annual arithmetic mean concentration - micrograms per cubic meter	80	60	-	-
Maximum 24-hour concentration not to be exceeded more than once per year - micrograms per cubic meter	365	260	244	212
Maximum one-hour average not to be exceeded in any 24-hour period - micrograms per cubic meter	-	1,300	458	398
Particulate				
Maximum annual geometric mean - micrograms per cubic meter	75	60	-	-
Maximum annual 99th percentile value at any sampling site - micrograms per cubic meter	-	-	-	-
Maximum in 24 hours not to be exceeded more than once a year - micrograms per cubic meter	260	150	75	17.2
Nitrogen Oxides				
Maximum annual arithmetic mean - micrograms per cubic meter	100	100	-	-
24-hour concentration not to be exceeded more than once per year - micrograms per cubic meter	250*	-	-	120.3

*recently proposed by EPA

6-2. Other Considerations on the Selection of Stack Heights

The idea of using different stack heights for different generating units is worthy to be investigated. The plant contributions of various pollutants can be predicted by the procedures similar to those for the plant with stacks of equal heights. Table 6-7 presents the approximate, maximum ground-level SO_2 contributions for various stack arrangements.

These calculations indicate that when the stacks do not have the same height at the plant site, the maximum ground-level SO_2 concentration contributed by the plant is always less than the sum of maximum ground-level concentrations of all stacks. However, the differences seem to be insignificant in this study.

The possibility of using one stack for two generating units was considered. Some necessary calculations were carried out. The results are presented in Table 6-8. It is seen that the idea of one stack for two units is attractive from an air pollution control viewpoint. The arrangement generally results in the maximum rise of the hot gas, the increase in the plume's ability to pierce inversions and the maintenance of reasonable exit velocity. Offsetting these recognized advantages are many factors such as the loss of operational flexibilities. This investigation is intneded to evaluate these arrangements only in terms of SO_2 dispersions.

The effects of stack heights on the maximum ground-level SO_2 concentrations was investigated. Table 6-9 indicates the effects of stack heights on the maximum ground-level SO_2 concentrations. One stack is designed for one generating unit. All numerical results are expressed in terms of parts per million (ppm). The corresponding limit in the State of Arkansas is 0.20 ppm.

Table 6-7

Max. Ground-Level SO_2 Concentrations[1]
Contributed by the Plant

Case No.	Arrangements	Max. Ground-level SO_2 Concentration[2]	Safety Factor[3]
1.	4 stacks (each 700 ft)	633.6	1.03
2.	4 stacks (each 800 ft)	561.6	1.17
3.	4 stacks (each 900 ft)	506.5	1.29
4.	4 stacks (two 600 ft and two 800 ft)	630.8	1.04
5.	4 stacks (three 600 ft and one 900 ft)	650.9	1.01

1. the allowable limit is approximately 655.3 ug/m^3 in the 10 minute sampling average.
2. all SO_2 concentrations are in terms of micrograms per cubic meters (10 min. sampling average).
3. safety factor is defined as the ratio of allowable limit to the calculated maximum concentration.

Table 6-8

Stack Heights Under Various Constraints

No.	Constraints	Calculated Stack Height, ft.
1.	One stack for one generating unit and 4 units at the site	800
2.	One stack for one generating unit and 6 units at the site	1,100
3.	One stack for two generating units and 4 units at the site	800
4.	One stack for two generating units and 6 units at the site	900

Table 6-9

Effects of Stack Height on the Maximum Ground-Level SO_2 Concentrations

Stack Height ft	Max. ground-level SO_2 concentration - ppm (the sampling time=0.5 hr.)		
	CASE 1	CASE 2	CASE 3
800	0.0433	0.173	0.259
900	0.0396	0.158	0.237
1000	0.0363	0.145	0.217
1100	0.0336	0.134	0.200

CASE 1 - Single stack

CASE 2 - Four units at the plant site

CASE 3 - Six units at the plant site

It should be emphasized that the maximum value would occur only at a certain downwind distance and at the critical wind speed. As the stack height increases, the reduction of SO_2 ground-level concentrations would diminishingly decrease.

An examination of any mathematical model for predicting the ground-level concentrations of SO_2 would reveal an importance of plume rise calculations. With the emission data of generating unit in the case study, it was found that an overestimate of plume rise by 25% will lower the prediction of the maximum ground-level SO_2 concentration by 17.5%. It is this fact which makes it necessary to compare the Holland's equation used in this study with other plume rise equations.

The computational experiments were carried out. The results shown on Table 6-10 indicate that the Holland's equation is close to other equations reasonably.

Table 6-10

Comparison of Plume Rise Equations - meters

Computational Ex. No.	Holland Equation	Carson and Moses Eq.	Lucas, Moore, & Spurr Eq.	Concawe Equation
1.	197.2	184.4	171.4	243.0
2.	239.0	222.0	249.0	277.0
3.	199.5	209.8	326.8	254.0
4.	635.0	654.0	334.9	554.0
5.	126.0	118.0	144.9	178.0

6-3. Ground Level SO_2 Concentration at Various Distances from Stack

The ground-level SO_2 concentration beneath the axis of a plume would vary as the downwind distance from stack increases. In general, the concentration will first increase, and then decrease gradually. Naturally the variation of ground-level concentrations would depend upon many factors such as the atmospheric stability conditions, wind speed and stack design parameters. Table 6-11 shows some of the calculated results for the stack of recommended height (800 ft.) under an unstable atmospheric conditions. It is seen that at each wind speed there is a critical downwind distance at which the maximum concentration occurs. Also, for each stack height there is a critical wind speed at which the maximum ground-level concentration will appear. In this case, the critical wind speed is approximately equal to 8 meters/sec. and the maximum ground-level SO_2 concentration occurs at the downwind distance 3 km.

The ground-level SO_2 concentration would not only vary with the downwind distance from the stack, but also vary with the cross wind distance from the plume centerline. As the crosswind distance from the plume centerline increases, the ground-level SO_2 concentration would decrease rapidly. The relationship is similar to the Gaussian distribution function.

The vertical variation of SO_2 concentrations has been determined in this study. It was found that the SO_2 concentration level would decrease as the vertical distance from the axis of the plume increases. It means that the ground-level SO_2 concentration is always lower than that at the center of the plume. However, in the selection of stack height, it is the maximum ground-level SO_2 concentration which will have an influence.

Table 11

Ground-Level SO_2 Concentrations
At Various Downwind Distances - ug/m^3

km Distance from Stack	Wind Speed (m/sec.) 5.0	6.0	7.0	8.0	9.0	10.0
2.0	22.8	31.9	61.0	76.6	87.1	96.1
3.0	114.4	131.9	138.9	140.4	138.4	136.7
4.0	139.3	135.9	130.5	122.9	115.3	109.0
5.0	125.3	116.5	105.1	95.7	87.6	81.1
10.0	49.2	41.9	36.4	32.2	28.7	26.1
20.0	13.2	11.0	9.5	8.3	7.4	6.7
50.0	2.5	2.1	1.8	1.6	1.4	1.3

6-4. Particulate Matter Levels

The Environmental Protection Agency (EPA) established the emission standard for particular matter 0.1 lbs/million Btu. On this basis the emission rate of particulate matter will be approximately 907.8 lbs/hr. for each generating unit. This is 8.16% of the SO_2 emission rate. Since the stack height has been sized on the basis of allowable ground-level SO_2 concentration (526 ug/m^3 on a 30 min. average sampling), it is expected that the maximum particulate concentration level from four stacks will not be higher than 8.16% of this limit or 42.9 ug/m^3 on a 30 min. average. Compared with the State limits (an average of 75 ug/m^3 for any 24 hour period or 150 ug/m^3 for any thirty (30) minute average), this estimated maximum level should be acceptable.

It is planned that a precipitator will be installed for each unit. Therefore the number of particles larger than 60 microns in diameter in the downwind direction is expected normally not to exceed the state limit. The State limit is 120 per square centimeter for 24 consecutive hours.

The particular fallout contributed from the four stacks has been estimated with the assumption that all particulates matter will fall to the ground within 10 miles of the plant. The average fallout is approximately 4.16 tons per square mile per month. The Arkansas State Standard is 15 tons per square mile per month.

It should be pointed out that the actual emission rate of particulate matter in the power station under consideration is much lower than that estimated above. The latest estimate is approximately 400 lbs/hr. for each unit. If this is the case, the particulate matter level will be greatly reduced.

6-5. Concentration of Nitrogen Oxides

It seems that the State of Arkansas has not established Ambient Air Standards for NO or NO_2. For information purposes some estimates have been made and the results are presented as follows:

The emission rate of nitrogen oxides was estimated on the basis of the EPA emission standard and found approximately 6,354 lbs/hr. On a mass basis this is 57.2% of the SO_2 emission rate.

Procedures for calculations of ground-level NO_x concentrations are identical to those for SO_2. The ground-level NO_x concentration are, therefore, equal to the SO2 concentrations multiplied by 0.572 (unit of ug/m^3 rather than ppm must be used). With this relationship it is estimated that the maximum possible NO_x concentration level contributed from the four stacks is not higher than 139 ug/m^3 on the 24-hour average.

The Environmental Protection Agency (EPA) has not set any limit for ground-level concentration of NO_x. But it proposed (according to the information available in 1971) that the 24-hour maximum average be 250 ug/m^3. Compared with the proposed limit, the maximum ground-level NO_x concentration calculated in this study should be acceptable.

6-6. Closing Remark

The philosophy adopted for selection of the stack height was to calculate the ground-level concentration of the various emission constituents and to select the height of stack which would assure that the regulatory standards would not be exceeded. However, this philosophy will have the following implications:

1. In the area where the power plant is situated, the State government and community will have 100% of the air quality standards pre-empted by this new source. It means that the area will have no more industrial and other developments that may emit the regulated pollutants such as SO_2.
2. The second implication is that the air of the region is not polluted by the regulated pollutants. The level of present pollution, referred to as the background level, is assumed to be zero.
3. The third implication is that the dispersion model developed for an unimpeded level terrain, is completely valid for the present project.

Realistically, the regulatory agency and the community may wish to invoke the foregoing constraints. If and when this is the case, the correction factor for determination of the allowable air quality standards should be applied.

In this study it was found that the sulfur dioxides emitted from the plant is slightly higher than that specified by the Environmental Protection Agency (EPA). If this emission standard has to be satisfied, additional steps should be taken both in design and in operation.

The accuracy of dispersion calculations is largely dependent with the availability of wind information for the plant site. In addition to the data on the wind speed and direction, the variation of the horizontal wind with height must be available. From this data, the standard deviations (both azimuth and elevation angles) of wind direction fluctuation are calculated and with them, the diffusion parameters in the dispersion model are determined. It should be stressed here that the vertical wind speed profile is also affected by changes in the underlying terrain and the atmospheric thermal stability.

In the study, we have neither information about the wind variation with height, nor any data from which the diffusion parameters can be determined. Because of this lack of weather data, we have simply made two assumptions in these respects:

1. no variation of wind speed and direction with height.
2. diffusion parameters are those specified in the stability class B.

Among many factors which affect the dispersion of effluents, one is the local atmospheric stability. The atmospheric stability is mainly influenced by the atmospheric temperature structure at the plant site. It varies from season to season, and from hour to hour within a day. Naturally, the atmospheric stability changes from area to area. It also varies with altitude. To have a complete picture of atmospheric stability at the plant site, details of the local temperature structure must be available. Ideally, the time cross section of daily temperature can be prepared from the local weather data. With this information it is quite easy to predict the environmental lapse rates at different

altitudes, size of inversion layers (which may exist simultaneously at different altitudes), and the depth of the convective layer. All these are needed for an accurate prediction of ground-level concentrations. With this data, one can also predict the ground-level concentrations and their frequencies of inversion breakup and trapping fumigations.

For this study we lacked the local temperature data as described above. We estimated the local atmospheric stability by using a near-by airport weather information and the method of stability classification suggested by D.B. Turner.

A multi-stack system generally presents the problems which are not encountered in the single-stack system. One of them is the inference among the plumes from the stacks. It is intuitively obvious that at the distance very close to the stacks, the plumes may retain their individual pattern and at a longer distance, they would emerge together. Generally, the plumes from multiple stacks will rise higher than that from one of them. This is especially true when the wind direction is parallel to the row of stacks. However, methods for a quantitative prediction are not yet available.

In addition to the plume interferences, the multi-stack system has another problem. That is the aerodynamic downwash phenomenon between the stacks. Because there is no theory to predict their effects on the ground-level concentrations, the scale model experiments are generally needed for economic design of a multi-stack system.

Additional calculations were made after this case study was completed. These supplementary studies include 1. stack arrangement 2. stack spacing distance 3. preliminary checks on the average annual concentration. All these are presented in Appendix B. The following are the recommendations on further works:

1. The power company should work with the governmental agencies and determine the allowable air quality standards for this design.
2. A post-construction measurement program should be formulated and carried out. The measurements include plume rises, ground-level concentrations, temperature and wind variations and others suggested in this section. The results of this program will be very helpful to the design of the stacks for future units at the same site.
3. Some scale model experiments should be formulated and conducted. The data obtained in these experiments are needed for economic design of a multi-stack system. It is not surprising that the saving in construction will offset the cost of the experimental program.
4. Previous experiences in design of multi-stack systems should be utilized. Visits to the Dayton Power and Light Company and others may be helpful.

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APPENDIX A

Atmospheric Stability Categories

In the determination of stack height and predictions of concentration levels of pollutants the area atmospheric information is needed. The Turner's mathematical model requires that the atmospheric stability be classified into six categories. They are shown in the following tables: Class A is the most unstable, Class F the most stable class considered here. Night refers to the period from one hour before sunset to one hour after sunrise. Class D is generally used when the atmospheric stability is in a neutral state.

In this study we consider that the Class B would mostly fit the description of meteorological conditions for the Station under consideration. This choice would provide some safety margin for the stack performance when the atmospheric conditions become less unstable or neutral.

Table A-1 - Stability Categories

	Day			Night	
Surface Wind Speed(at 10 m) m/sec.	Incoming Solar Radiation			Thinly Overcast or	
	Strong	Moderate	Slight	4/8 Low Cloud	3/8 Cloud
2	A	A-B	B		
2 - 3	A-B	B	C	E	F
3 - 5	B	B-C	C	D	E
5 - 6	C	C-D	D	D	D
6	D	D	D	D	D

APPENDIX B

B-1. Stack Arrangements

This section presents the results of a supplementary study for the stack project. It includes a selection of stack height for the units No. 5 and No. 6, and a prediction of maximum SO_2 ground-level concentration. These two stacks are to be added to the original stack system (four 800 ft. stacks). The in-line and staggered stack arrangements height.

In-Line Arrangement

The stack height for the unit No. 5 and No. 6 is recommended to be at least 900 feet at this time. When these two stacks are added to the previous four, the maximum SO_2 ground-level concentration contributed by the whole plant will be in the range of 0.177 - 0.200 ppm on a 30 min. sampling average. This level does not exceed the limits specified by the EPA and the State of Arkansas.

Table B-1 shows the maximum plant contributed SO_2 ground-level concentrations for various stack heights for units No. 5 and No. 6.

Staggered Arrangement

The sketch of the staggered arrangement is shown in Figure B-1. It was found in this study that the staggered arrangement would not significantly reduce the maximum SO_2 gound-level concentration. Table B-2 indicates the maximum SO_2 ground-level concentrations when the units No. 5 and No. 6 have the stack height of 900 feet (the first four were assumed to be 800 feet in height).

In this study the normalized SO_2 ground-level concentrations were calculated. The normalized value was defined as the ratio of the ground-level concentration to the maximum ground-level concentration at the same downwind distance. Some of the calculated results are shown in Table B-3. It is seen that all these normalized values are quite close to 1.0 in the range of interest. Thus, it can be concluded that the staggered arrangement shown in Figure B-1 will not produce the ground level concentrations significantly different from those by the in-line arrangement.

Table B-1

The maximum plant contributed SO_2 ground-level concentration

(In-line arrangement)

Stack Height for the first four unit ft.	Stack Height for the units No. 5 and No. 6 ft.	Max. Plant contributed SO_2 ground-level concentration ppm
800	800	0.183-0.206
800	900	0.177-0.200
800	1000	0.172-0.195
800	1100	0.168-0.190

Table B-2

The Maximum Plant Contributed SO_2 ground-level concentration

(Staggered arrangement)

Distance between the two stack rows (meter)	Max. plant contributed SO_2 ground-level concentration* (ppm)
0	0.177-0.200
100	0.176-0.198
150	0.174-0.197
200	0.173-0.196
250	0.172-0.193
300	0.171-0.191

* Assume that the max. concentration occurs approximately at the downwind distance 4 km.

Table B-3

Normalized SO_2 Ground level Concentrations

Downwind Distance (meter)	Cross-wind Distance from the plume cenerline (meter)	Normalized SO_2 Ground level Concentration
3000	0	1.000
	100	0.972
	150	0.937
	200	0.891
	250	0.840
	300	0.777
4000	0	1.000
	100	0.984
	150	0.964
	200	0.937
	250	0.904
	300	0.864
5000	0	1.000
	100	0.989
	150	0.974
	200	0.956
	250	0.930
	300	0.904

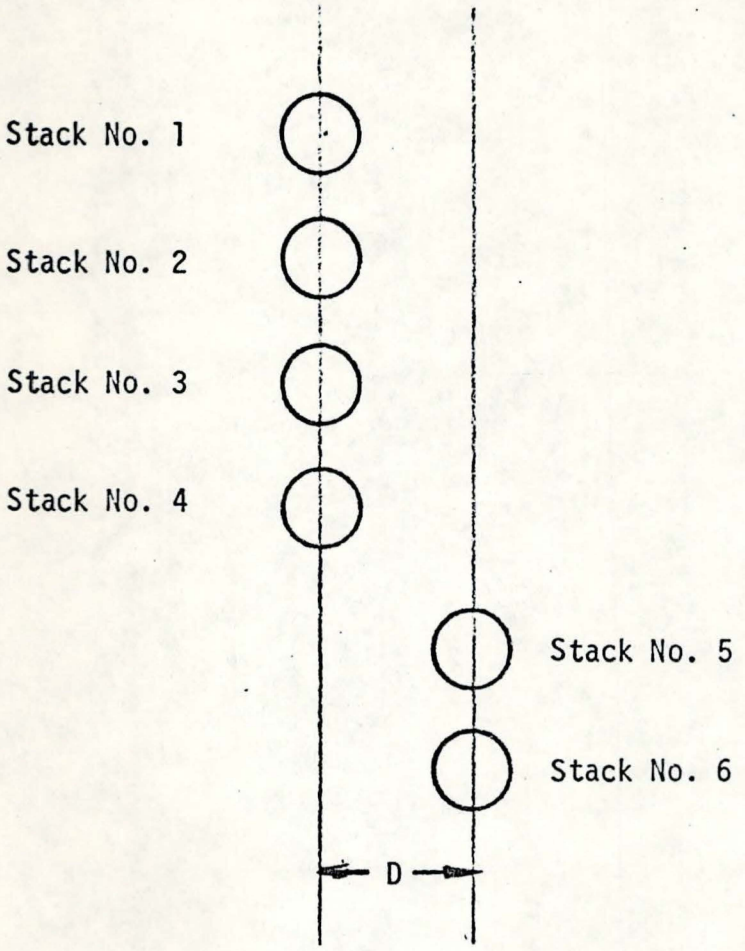

Fig. B-1 Staggered arrangement

B-2. Stack Spacing Distance

In the stack project the ground-level SO_2 concentrations were calculated with the assumption that the effects of spacing distance between the stacks could be neglected. This supplement is intended to confirm, by numerical calculations, the validity of this assumption.

Table B-4 indicates the calculated ground-level SO_2 concentrations at the downwind distances. These were done under three different spacing conditions.

1. Zero spacing
2. 300 feet in spacing
3. 600 feet in spacing

It is seen in Table B-4 that the maximum concentration values in both cases (300 feet and 600 feet spacing) are slightly lower than that calculated with the assumption of zero spacing. For instance, assuming 300 feet in spacing would only lower the prediction of the maximum ground-level SO_2 concentration by 1.08%. It should be pointed out that a linear interpretation was used in preparation of Table B-4. If more accurate techniques were used, the difference of these maximum concentrations would be further reduced.

Different assumption on the spacing distance will change the calculated results on the SO_2 distributions. Table B-4 shows that the critical location (at which the maximum ground-level SO_2 concentration would occur) will move away from the plant in the downwind direction as the spacing distance increases.

The selection of stack height is based on the calculation of maximum SO_2 ground-level concentration. And this maximum value has been found quite insensitive to the assumption on the spacing distance between the stacks. For the present purpose, the original assumption should be acceptable.

Table B-4

EFFECT OF SPACING DISTANCE BETWEEN THE STACKS ON THE GROUND - LEVEL SO_2 CONCENTRATIONS.**

(Micrograms per cubic meter)

Downwind distance from the 1st stack	Spacing Distance between the Stacks (feet)		
(km.)	0.0	300	600
2.5	448	418	388
2.6	472	442	410
2.7	494	465	433
2.8	516	486	455
2.9	540	510	478
3.0	560*	532	501
3.1	555	546	516
3.2	548	554*	529
3.3	540	550	538
3.4	534	543	543*
3.5	528	536	543
3.6	520	528	539
3.7	512	521	532
3.8	505	514	525

** Wind speed = 8 m/s and wind direction is either due north or due south.

* Maximum value.

B-3. Preliminary Checks on the Average Annual Concentration

This section presents a calculational method for prediction of average annual concentration. It also includes some estimates of average annual concentrations for the power station under consideration.

The average annual concentration can be predicted by the following equation:

$$\bar{\chi}(x, \theta) = \sum_s \sum_n \left\{ \frac{2\, Q\, F(\theta, s, n)}{\sqrt{2\pi}\, \sigma_{zs}\, U_n\, (\frac{2\pi x}{16})} \quad \text{Exp}\left[-\frac{1}{2} \left(\frac{H_u}{\sigma_{zs}}\right)^2 \right] \right\}$$

where $F(\theta, s, n)$ is the frequency during the period of interest that the wind is from the direction θ, for the stability condition s, and the wind speed class n.

σ_{zs} is the vertical dispersion parameter evaluated at the distance x for the stability condition s.

U_n is the representative wind speed for the class n.

H_u is the effective height of release for the wind speed U_n.

The above equation indicates that the average annual concentrations can be predicted by calculating the concentrations for specific climatological conditions and then, weighing each concentration by its relative frequency of occurance. The calculations will be straightforward, but lengthy. The frequency of occurrence which is a function of three variables (wind direction, wind class and stability class) has been prepared with

the available climatological data. These were presented in Table 6-5.

This study indicates that a compliance with the 24-hour air quality standards will generally assure a compliance with the annual limits. For the Power Station under consideration the wind rose is relatively uniform in all directions. The highest frequency is 10.7% for WSW wind (16 wind directions were taken in this study). Under these conditions, even the maximum 24-hour SO_2 concentration is reached every day (the calculated value is 212 micrograms per cubic meter), the highest annual arithmatic-mean SO_2 concentration would be only equal to 22.7 micrograms per cubic meter. It should be pointed out that the actual annual SO_2 concentration will be much less than the above estimate.

The Environmental Protection Agency (EPA) has established an annual average concentration for SO_2. The primary and secondary limits are respectively 80 and 60 micrograms per cubic meter. Compared with these limits, the estimate of annual average SO_2 concentration should be quite acceptable.

As pointed out in the case study, the concentrations of NO_x are in all cases equal to the SO_2 concentrations multiplied by 0.572. With this relationship it is estimated that the maximum possible annual average NO_x concentration level will be 13 microgram per cubic meter. Compared with the EPA limit, this estimated level is only 13% of the maximum allowable.